Baryogenesis from Gravitational Decay of TeV-Particles in Theories with Low Scale Gravity

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Abstract

In models with the fundamental gravity scale in the TeV range, early cosmology is quite different from the standard picture, because the universe must have arisen at a much lower temperature and the electroweak symmetry was probably never restored. In this context, baryogenesis appears to be problematic: if the involved physics is essentially that of the Standard Model, "conventional" non-conserving baryon number processes are completely negligible at such low temperatures. In this paper we show that the observed matter-antimatter asymmetry of the universe may be generated by gravitational decay of TeV-mass particles: such objects can be out of equilibrium after inflation and, if their mass is of the same order of magnitude as the true quantum gravity scale, they can quickly decay through a black hole intermediate state, violating global symmetries, in particular, baryon number. In this context, we take advantage of the fact that the "Sakharov conditions" for baryogenesis can be more easily satisfied with a low fundamental scale of gravity.

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1 Introduction

The mechanism of generation of the observed matter-antimatter asymmetry in the universe is an open problem in modern cosmology and a clear sign of new physics beyond the Standard Model. Many possibilities have been proposed [1], but at present there is no experimental evidence in favor of one model over another. In addition, unluckily, the models are often based on assumptions difficult to test, since the involved physics is at such high energies as to be unreachable in future laboratories on the Earth.

We will consider baryogenesis scenarios based on low scale gravity with the fundamental Planck mass, M_*, in the TeV range. As we shall see in what follows, the baryogenesis scenarios in models with a low gravity scale encounter some additional problems, because of an expected very low reheating temperature of the universe, and, therefore, additional exotic assumptions, e.g. time variation of fundamental constants, are usually needed. In this context, on the other hand, we will show that the "Sakharov conditions" for baryogenesis can be more easily satisfied with a low fundamental scale of gravity. In addition, the mechanism may operate with the minimal particle content (only known quarks) or with a minor extension to low energy supersymmetry.

In the standard framework of general relativity, there is probably no realistic possibility to ever observe gravitational interactions in particle physics. This is due to the fact that there are apparently two distinct fundamental energy scales in nature which are different by many orders of magnitude, namely, the Planck mass $M_{Pl} \sim 10^{19}$ GeV, which sets the energy when gravity becomes comparable to gauge interactions, and the electroweak scale of the Standard Model of particle physics, $M_{EW} \sim 10^3$ GeV, which is accessible in lepton and hadron colliders.

However, the interpretation of M_{Pl} and M_{EW} as two fundamental energy scales may be incorrect because the previous assertion is based on the non-trivial assumption that gravity behavior is unchanged down to the Planck length $L_{Pl} \sim 10^{-33}$ cm. However, all we know from experimental tests of gravity is its force at the present time on macroscopic distances, that is in the range 10^{-2} cm – 10^{28} cm.

Loopholes have been found in recent years. For example, in models with extra dimensions [2]-[5] the true fundamental gravity scale can be as low as a few TeV, and the large Planck mass is then merely an effective long-distance 4-dimensional parameter. For a recent review see [6]. In these scenarios, gravity becomes phenomenologically interesting for high energy physics and we may observe and study quantum gravity phenomena at future colliders.

Another suggestion to explain the electroweak-gravitational hierarchy in a natural way in the 4 dimensional world was recently put forward in Ref. [7]. It is assumed that there exists a scalar field Φ with nonminimal coupling to the curvature, $RV(\Phi)$. The initial value of the function $V(\Phi)$ is supposed to be in electroweak scale, i.e. about $(\text{TeV})^2$, while due to dynamical evolution of $\Phi(t)$ it may reach the asymptotic Planck value, $V(\Phi_\infty) = M_{Pl}^2$.

While TeV-gravity is a fascinating possibility from the point of view of particle phenomenology, its cosmology may be problematic. In fact we can reasonably expect that in such models the maximum temperature of the universe never exceeded a few TeV, since the concept of spacetime itself exists only for temperatures below the fundamental gravity scale. In fact we often find the reheating temperature after inflation to be significantly lower. Consequently, ordinary cosmology commenced at temperatures so low that electroweak symmetry breaking $M_{EWSB} \sim 300$ GeV never took place in the early universe. Since at the moment we have no reliable information about the universe before it was 1 s old, i.e. before primordial nucleosynthesis, there are no direct contradictions with the assumption of TeV gravity. However, baryogenesis is quite difficult in these models, because to this end a mechanism working at relatively low energies is needed and presently we do not know anything suitable in the context of the Standard Model. In particular, violation of baryon number (B) conservation below the electroweak phase transition is completely negligible in the standard theory and this seemingly forbids any realistic baryogenesis scenario in the case of low scale gravity.

On the contrary, a low fundamental scale of gravity opens a new possibility for TeV scale baryogenesis, because the gravitational interaction itself can naturally break B-conservation. In this paper we consider gravitational decays of heavy particles as a mechanism for low-temperature baryogenesis. The details of the heavy particle decays are irrelevant. Instead, the key feature is that the decays are mediated by virtual black holes (BHs), which (according to common belief) can decay/evaporate with violation of global $U(1)$-quantum numbers including baryonic charge.

The possibility that BH evaporation could create the matter-antimatter asymmetry of the universe was suggested in Ref. [8] and considered in detail in Refs. [9] and [10]. The scenario was criticized in Ref. [11] on the basis that BH evaporation produces a thermal equilibrium state; yet, in the absence of CPT violation, a departure from thermal equilibrium is needed in order to produce an excess of particles over anti-particles. In response to this criticism, although the particle emission due to Hawking radiation at the BH horizon is indeed thermal, the equilibrium distribution is distorted after particle propagation in the gravitational field of the parent BH [12] and their mutual interactions [9]. In any case, in this paper we consider decay rather than BH evaporation. We will not deal with thermal Hawking radiation [13], a semiclassical process that can be realized only for "large" BHs. Instead, the decays considered here are essentially quantum gravity phenomena, with a small number of final particles not emitted with a thermal spectrum. Other criticisms may arise if, believing in the information preserving BHs picture, one were to argue that baryon number is not violated. However, a rigorous proof is lacking and, on the contrary, very reasonable arguments suggest that global quantum numbers are not be conserved [14].

The basic idea of the baryogenesis scenarios considered here is that TeV mass particles (the mass of the fundamental gravity scale) decay gravitationally via intermediate BHs; these decays violate baryon number. The essential ingredients of these baryogenesis scenarios are the three standard "Sakharov conditions" [15]. We stress that these conditions are *easier* to satisfy with a low fundamental scale of gravity. The first criterion, baryon number violation, is mediated by virtual BHs which can violate global quantum numbers; such gravitational effects are inversely related to the effective Planck mass and hence are stronger for low fundamental gravity scales. The second criterion, CP-violation, which is negligible at high temperatures in the Minimal Standard Model, may be much larger in TeV gravity models. First, the effective temperatures can be quite small, about a few hundred MeV, and second, we consider time variation of the quark masses and their mixing angles. The third criterion, deviation from thermal equilibrium, which is normally negligible at electroweak energies, might be amplified by a much faster Hubble rate, which in turn is enhanced by a very small Planck mass. These features may lead to very efficient baryogenesis at relatively low energies.

The content of the paper is as follows. We briefly review TeV-gravity models in Sec. 2 and the related early cosmology in Sec. 3. In Sec. 4 we present our baryogenesis model and give an estimate of the resultant matter-antimatter asymmetry. We conclude in Sec. 5.

2 TeV-gravity models

There has been a great deal of interest recently in models with a low scale for gravity, especially since they may provide a resolution to the perplexing hierarchy problem in particle physics. Two possibilities have been discussed for TeV-scale gravity: 1) large extra dimensions and 2) time-varying Planck mass. We briefly review these ideas and their experimental consequences.

Large Extra Dimensions: In 1998 Antoniadis, Arkani-Hamed, Dimopoulos and Dvali proposed a "geometric" solution to the hierarchy problem of high energy physics, where the observed weakness of gravity (at long distances) would be related to the presence of large compact extra dimensions [2, 3]. Motivated by string theory, the observable universe would be a 4-dimensional brane embedded in a (4+n)-dimensional bulk, with the Standard Model particles confined to the brane, while gravity is allowed to propagate throughout the bulk. In such scenarios, the Planck mass M_{Pl} becomes an effective long-distance 4-dimensional parameter and the relation with the fundamental gravity scale M_* is given by

$$M_{Pl}^2 \sim M_*^{2+n} R^n \,, \tag{1}$$

where R is the size of the extra dimensions. If these extra dimensions are "large", i.e. $R \gg M_{Pl}^{-1} \sim 10^{-33}$ cm, then the fundamental gravity scale can be as low as a few TeV and therefore of the same order of magnitude as M_{EW}. If we assume $M_* \sim 1$ TeV, we find:

$$R \sim 10^{(30/n)-17} \text{ cm} \,. \tag{2}$$

In this approach, however, the hierarchy problem is not really solved but shifted instead from the hierarchy in energies to a hierarchy in the size of the extra dimensions which are much larger than 1/TeV $\sim 10^{-17}$ cm but much smaller than the 4-dimensional universe size.

The case $n = 1$ is excluded because from Eq. (2) we would obtain $R \sim 10^{13}$ cm and therefore strong deviations from Newtonian gravity at solar system distances would result. For $n \geq 2$, $R \lesssim 100$ μm and nowadays we have no experimental evidence against a modification of gravitational forces in such a regime [16]. Interesting variations of these models can lower the fundamental gravity scale with the use of non-compact extra dimensions [5].

If gravitational interactions become strong at the TeV scale, quantum gravity phenomena are in the accessible range of future experiments in high energy physics. In particular, there is a fascinating possibility that hadron colliders (such as LHC) will be BH factories (for a review, see e.g. Ref. [17], criticisms can be found in Refs. [18, 19]). From the classical point of view, we expect BH production in collision of two particles with center of mass energy $\sqrt{s}$, if these particles approach each other so closely that they happen to be inside the event horizon of a BH with mass $M_{BH} \approx \sqrt{s}$. Semiclassical arguments, valid for $M_{BH} \gg M_*$, predict the BH production cross-section

$$\sigma \approx \pi R_{BH}^2(M_{BH}) \,, \tag{3}$$

where $R_{BH}(M_{BH})$ is the horizon radius of a BH of mass M_{BH}.

Time-varying Planck mass: An alternative origin of a fundamental TeV scale for gravity involves a time-varying Planck mass. The idea that the value of the Planck mass has evolved with time, and was much lower in the early universe, goes back to Dirac and his "large number hypothesis" [20]. This idea was then developed by other authors as a complete field theory of gravitation and culminated in the Brans-Dicke theory [21] and in more general scalar-tensor theories of gravity [22]. These models have been extensively studied in the literature, but only recently [7] has it been stressed that they are capable of solving the hierarchy problem. In [7] the authors take

$$V(\Phi) \sim M_*^2 f(\Phi) \,, \tag{4}$$

where $M_* \sim M_{EW}$ is the only fundamental scale of the theory and $f(\Phi)$ a dimensionless function of Φ. The huge gap between M_{Pl} and M_{EW} we observe today is explained with a temporal evolution of the scalar field $\Phi(t)$ in the 4-dimensional spacetime. As a modification of the the model of Ref. [7] we can consider, for example, an exponential potential

$$V(\Phi) = V_0 \exp[W(\Phi)] \tag{5}$$

with e.g. $W = (\Phi/\mu)^2 - \lambda(\Phi/\mu)^4$. A reasonably small $\lambda \sim 10^{-2}$ could ensure the required hierarchy of 16 orders of magnitude between the Planck and electroweak scales. We plan to present elsewhere a detailed study of the evolution of Φ and the features of the corresponding cosmology.

If the Planck mass depends on the value of a scalar field Φ and today has its usual large value with $M_{Pl} \gg M_{EW}$, then gravitational interactions should be negligible in particle physics today, as in the standard theory. In particular, the next generation of colliders will not be able to produce BHs. Nevertheless, in the early universe, when Φ has not yet evolved to its present value, non-negligible quantum gravity effects might be effective. Baryogenesis, in particular, could take place as is described in the present paper.

3 Early universe in theories with low scale gravity

According to the standard hot Big Bang model, which is described by the Friedmann equation, as we look backwards in time, the universe was hotter and hotter. According to common belief, such equations, obtained from classical general relativity, break down when we reach the temperature $T \sim M_{Pl}$ and curvature $R \sim M_{Pl}^2$, at which point quantum gravity phenomena become important: it is reasonable to expect that the universe has never exceeded these values of curvature and temperature and that the initial singularity in the Robertson-Walker metric is a drawback of the classical theory. Supplementing the Big Bang, in order to resolve difficulties such as the horizon and flatness problems, the inflation paradigm [23] was introduced. Inflation requires a superluminal expansion rate of the very early universe followed by a period of reheating. All the relics we do not want to be abundant in the present-day universe (such as superheavy objects capable of overclosing the universe) must be produced before inflation, so they can be strongly diluted. On the other hand, events which must have left traces (such as the baryogenesis) must take place after inflation.

If the true fundamental gravity scale is in the TeV range, the maximum conceivable temperature of the universe is of the same order of magnitude and the reheating temperature is probably too low to allow for the electroweak phase transition. Early universe cosmology is deeply modified and the generation of the matter-antimatter asymmetry becomes a real challenge. Popular scenarios, operating at the GUT scale, $M_{GUT} \sim 10^{16}$ GeV, or at the electroweak symmetry breaking with $T \sim$ TeV, cannot work. New mechanisms, efficient at lower energies, are needed. We note that chain inflation [24] with the QCD axion also leads to a low reheat temperature, $T \sim 10$ MeV.

As for models with large extra dimensions, the situation is even worse, because the reheating temperature is usually expected to be well below M_*. In fact, at high temperatures a copious production of gravitons into the bulk took place; if we require the cosmological expansion rate compatible with the observations of primordial light elements created when the temperature of the universe was $T_{bbn} \sim 1$ MeV, we obtain a maximum temperature (usually assumed as upper bound for the reheating temperature after inflation) [25]

$$T_{max} \lesssim M_* \left(\frac{T_{bbn}}{M_{Pl}}\right)^{1/(n+2)} . \tag{6}$$

For $n = 2$ we obtain $T_{max} \lesssim 10$ MeV, whereas $n = 7$ leads to $T_{max} \lesssim 10$ GeV. At such low temperatures standard scenarios of baryogenesis are impossible.

Constraints on the time variation of the Planck mass can be derived from different cosmological and astrophysical considerations (for a review, see e.g. Ref. [26]). The most stringent bound comes from the big bang nucleosynthesis. The analysis of light elements production requires that when the universe temperature was around 1 MeV the Planck mass had to be essentially frozen at its present value: the allowed deviation from the value that we measure today should be less than 5% [27].

In this paper we will investigate baryogenesis with TeV gravity scales and low reheating temperature in a model independent way, rather than distinguishing between models with extra dimensions from models with a time variable Planck mass. The essential physics is the same. General features of baryogenesis with a low gravity scale, based on enumeration of possible non-renormalizable B-violating operators in an effective low energy Lagrangian, are described in Ref. [28]. We note that some alternative ideas for baryogenesis at extremely low temperatures have been considered earlier (e.g. [29]).

4 Mechanism of baryogenesis

In order to generate a cosmological matter-antimatter asymmetry in an initially symmetric universe, usual baryogenesis scenarios assume CPT invariance and require the so-called "Sakharov conditions" [15]:

1. baryon number non-conservation,
2. violation of C (charge conjugation) and CP (charge conjugation combined with parity) symmetries,
3. deviation from thermal equilibrium.

For a discussion, see e.g. [1, 30, 31].

Here we consider a possible baryogenesis mechanism in models with a fundamental gravity scale M_* in the TeV range. In particular we discuss the original scenario of out-of-equilibrium decay of heavy particles, X, appropriately modified to the case of TeV scale gravity. In this section we briefly describe the main features of the scenario and emphasize the advantages of TeV scale gravity in satisfying the "Sakharov conditions" required for any baryogenesis model. We will try to be as close to the Minimal Standard Model in particle physics as possible, though we do not reject a possible supersymmetric extension which may make baryogenesis more efficient. We will present also a more detailed realization of the three conditions in a concrete model.

1. *Baryon number violation:* In this paper we use gravitational effects that violate baryon number and we focus on the role of baryon-violating processes mediated by BHs. Since such gravitational effects are inversely proportional to a power of the effective Planck mass, a smaller fundamental gravity scale leads to more effective baryon violation. Thus a strong non-conservation of baryonic charge is a generic feature of TeV gravity models. In fact, care should be taken to avoid too strong nonconservation of baryons to keep protons reasonably stable. On the other hand, this feature of an enhanced baryon number violation is favorable for cosmological baryogenesis.

2. *CP violation:* CP-nonconservation in the Minimal Standard Model is known to be very weak. At high temperatures it is proportional to

$$\epsilon_{CP} \approx (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) J_{PC}/T^{12} \tag{7}$$

where J_{CP} is the Jarlskog invariant

$$J_{CP} = \cos\theta_{12}\cos\theta_{23}\cos^2\theta_{13}\sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\sin\delta_{CP} \approx 3\cdot 10^{-5}\ . \tag{8}$$

Here θ_{ij} are mixing angles between different generations and δ_{CP} is the CP odd phase in the mass matrix. For $T \sim 100$ GeV, $\epsilon_{CP} \approx 10^{-19}$. Such a small magnitude surely demands some modification of the standard mechanism of CP violation to allow for successful baryogenesis.

Enhanced CP violation is possible assuming time dependent quark masses and mixings. Large CP violation may arise if quark masses were in the 100 GeV – TeV range in the early universe, with the mass differences of the same order of magnitude as the values of the masses. It is natural to expect that simultaneously with the masses, the mixing angles between quarks also changed and might possibly be of the order unity in the early universe, because both mixings and masses are determined by diagonalization of the same mass matrix which has different entries in the early universe and today. Since by assumption the quark masses were of the same magnitude in the early universe, all the mixings should be also of the same magnitude and quite probably close to unity.

On the other hand, if the temperature after inflation were much smaller than 100 GeV, ϵ_{CP} in Eq. (7) might not be so strongly suppressed. For example the reheating temperature in the MeV range would lead to CP-odd effects of the same order of magnitude as those observed in K or B mesons decays.

3. *Deviation from thermal equilibrium:* Here we focus on out-of-equilibrium decays of TeV scale particles as responsible for the generation of the baryon asymmetry. A sufficient cosmological abundance of such particles is not hard to imagine, they may e.g. be created during reheating after inflation as described further below.

The deviation from thermal equilibrium of non-relativistic decaying particles at a temperature T is much larger in TeV gravity than in the usual Planck scale one. Indeed, the deviation is determined by the ratio of the universe's expansion rate H to the reaction rate $\Gamma \sim g^2 m_X/2\pi$, where g is the coupling constant of X-particles to lighter decay products. Normally $g^2 \sim 0.1$. Hence, for example, in the standard cosmology where $H \sim \sqrt{\rho}/M_{Pl}$, with $\rho \sim T^4$ being the cosmological energy density, the parameter describing deviation from equilibrium at $T \approx m_X$ is

$$\delta_{neq} \equiv \frac{H}{\Gamma} \sim \frac{10^2\, m_X}{M_{Pl}}\ . \tag{9}$$

One can check that the magnitude of the baryon asymmetry generated in heavy particle decays is proportional to δ_{neq}, see e.g. Ref. [32]. In the case of electroweak masses and with $M_{Pl} \sim 10^{19}$ GeV, $\delta_{neq} \sim 10^{-15}$ and is negligibly small. On the other hand, if M_{Pl} depends on time and was a few TeV in the early universe, δ_{neq} might be easily of the order of unity. Thus a low fundamental gravity scale leads to out-of-equilibrium decays at much lower temperatures.

As for the braneworlds models, the situation is a little more subtle, since the related cosmology can be quite different from the standard one. For example, in the case of one extra dimension compactified on a circle, the effective 4-dimensional Friedmann equation is [33, 34]

$$H^2 \sim \left(\frac{\rho_{brane}}{48\pi M_*^3}\right)^2 + \frac{\Lambda_{bulk}}{48\pi M_*^3} \ , \tag{10}$$

where ρ_{brane} is the total energy density on the brane and Λ_{bulk} a possible bulk cosmological constant. Because of the compact nature of the extra dimension, we find that one of the dominant terms of the 00-component of the Einstein equations, i.e. the the square of the logarithmic derivative of the scale factor with respect to the extra dimension coordinate, is equal to $(a'/a)^2 \propto \rho_{brane}^2$. Hence, in order to recover the standard cosmology at low temperatures [35], ρ_{brane} can be split into the energy density of ordinary matter ρ and the brane cosmological constant Λ (which can be interpreted as the tension of the brane) and require

$$\Lambda_{bulk} = -\frac{\Lambda^2}{48\pi M_*^3} \qquad \Lambda = 6\,\frac{(8\pi)^3 M_*^6}{M_{Pl}^2} \ . \tag{11}$$

In this case the 4-dimensional Friedmann equation becomes

$$H^2 \sim \frac{8\pi\rho}{3M_{Pl}^2}\left(1 + \frac{\rho}{2\Lambda}\right) \ . \tag{12}$$

For $M_* \gtrsim 1$ TeV, the universe expansion rate is compatible with the big bang nucleosynthesis, but it is faster than the standard one at higher temperature, which is favorable for baryogenesis.

Another mechanism for breaking of thermal equilibrium commonly considered for electroweak baryogenesis is due to bubble formation in the first order electroweak phase transition. We note an advantage of our model, that such a first order electroweak phase transition is not necessary to create a large deviation from equilibrium. The first order electroweak phase transition is probably excluded by a heavy Higgs boson, if the mass of the latter is the same today and in the early universe, and in any case it can not be useful for baryogenesis in models with a fundamental gravity scale in TeV range: here the universe must have arisen at a much lower temperature and the electroweak symmetry was probably never restored.

There is also another possible source of the out-of-equilibrium physics required for successful baryogenesis created by the bubble collisions at the end of "chain inflation" as described further below. Out of equilibrium conditions for the bubbles are also easier to achieve in TeV gravity versus Planck gravity because of higher expansion rate in the first case.

4.1 "First Sakharov Condition": Baryon number violating decays

It was argued long ago [36] that gravity could induce processes with nonconservation of baryonic number. In particular, virtual Planck-mass BHs would induce proton instability and the expected decay width estimated by dimensional considerations would be

$$\Gamma_p \sim \frac{m_p^5}{M_{Pl}^4} \,. \tag{13}$$

For the normal Planck mass, $M_{Pl} \sim 10^{19}$ GeV, gravitational decays would be dangerous for very heavy particles only, with masses, say, in the interval $10^{10} - 10^{16}$ GeV; for discussion see Ref. [37]. On the other hand, with a smaller Planck mass in the TeV range, the baryon number violating processes would become much more efficient. In fact, Adams *et al.* [19] argued that experimental limits on the proton lifetime constrain the quantum gravity scale to be larger than 10^{16} GeV. A possible way to avoid too short life-time of proton is considered in our paper [38], where some other approaches are also discussed and the list of references is presented.

We have proposed there a conjecture that, just as in classical gravity, sub-Planck-mass BHs can only exist with zero local charge (electric or color) and zero angular momentum. In fact, according to classical general relativity in $3+1$ dimensions, a charged and rotating point-like particle with mass $m < M_{Pl}$ cannot form a BH, because its charge and angular momentum prevent the formation of the event horizon. Therefore, following our conjecture which forbids formation of a larger BH through violation of energy for a small time interval, the sub-Planck-mass initial states can form virtual BHs only with vacuum quantum numbers and baryon violating decays $\Delta B \neq 0$ should be noticeably suppressed. If we are interested in the decay of particles with nonzero spin and/or electric or color charge (such as all the "elementary" particles we know today), the formation of a Schwarzschild BH demands production of additional virtual particles and hence these processes can proceed only in higher orders of perturbation theory. Due to this conjecture, proton decay is suppressed to the point where it is in agreement with experimental bounds. In addition, we predict that neutron-antineutron oscillations and anomalous decays of muons, τ-leptons and K- and B-mesons can be quite close to the existing bounds and these processes may be found in the near future.

On the other hand, in this paper we are interested in the regime where the baryon violating decays are quite rapid. Although the rates are suppressed today, it is possible that they were much more rapid in the early universe. This is achievable if the mass of quarks changed with time and reached the true quantum gravity scale in the TeV range in the early universe: here a point-like particle with non-vanishing quantum numbers may form a BH and the branching ratio of B-violating decays may be noticeably enhanced. In particular, the rate of the B-nonconserving decay $t \to 2\bar{q} + l$ estimated in accordance with our work [38] would be about 10^{-10} in the present day universe. However, if the mass of the t-quark changed with time and reached the true quantum gravity scale in the early universe, the suppression mechanism of Ref. [38] does not work and the branching ratio could be even of order one (the initial state is no more below the true Planck mass and charged and rotating intermediate BHs are therefore allowed). This makes such decays promising for creation of the cosmological baryon asymmetry. These decays may be even more efficient if the masses of the weak intermediate bosons also change with time in such a way that W and Z would be heavier than the heaviest quark (in the early universe this is not necessarily the t-quark). In such a case the electroweak decays of the type $t \to Zq$ would be forbidden and the usual electroweak decays could proceed only through exchange of virtual W and Z bosons. The total decay width would be much smaller and the branching ratio of B-nonconserving decays would be strongly enhanced. For a possible mechanism of time variation of quark masses see below Subsection 4.2.

An alternative possibility to time variation of the quark masses is an existence of TeV elementary particles, for example supersymmetric partners of the Standard Model particles. The lightest SUSY particles are ordinarily stable against decays, because of R-parity, yet they may be able to produce intermediate BHs and consequently decay. If so, these particles might be responsible for baryogenesis but then unfortunately could no longer provide the dark matter of the universe.

TeV-particles produced out of thermal equilibrium after inflation can therefore decay fast via intermediate BHs and since the decay/evaporation of such objects does not conserve any global symmetry [14], these processes would violate the baryonic quantum number and might create the observed cosmological baryon asymmetry.

4.2 "Second Sakharov Condition": Violation of C and CP

When the intermediate BH state decays, the emitted particles interact with each other and, in order to generate a matter-antimatter asymmetry, C and CP violation must be present in their interactions. As we have already mentioned above, CP-violation in the standard model is extremely weak at high temperatures because of a small ratio of the quark mass difference to the temperature. One should remember that the weakness of CP-violation in the standard model is induced by the smallness of the Yukawa couplings between quarks and the Higgs field and the amplitude (7) is the same even in the unbroken phase when the masses vanish. One should keep in mind that for the usual electroweak baryogenesis the temperature should be above or around 100 GeV because sphalerons are not effective otherwise. However, in TeV scale gravity the temperature after inflation may be very low and the suppression (7) would be much milder.

A new source of CP-violation suggested recently [39] in a simple extension of the Standard Model may be also useful for the mechanism considered here.

Another interesting possibility is time variation of the quark masses. The idea was put forward in Ref. [40] but we suggest here a different realization. We assume that there exists one more scalar doublet χ, analogous to the Higgs one, which is strongly coupled to all quarks, $g_\chi \chi \bar\psi \psi$ with $g_\chi \sim 1$ (roughly speaking with the same strength as the usual Higgs is coupled to t-quark, or somewhat weaker but not as weak as the usual Higgs field, φ, is coupled to the light u and d quarks). If χ acquires vacuum expectation value in the TeV range only in the early universe, the quark mass differences and their masses could be all about TeV. Such unusual behavior can be achieved e.g. if χ has the potential with non-minimal coupling to curvature:

$$U(\chi) = \lambda |\chi|^4 + \xi |\chi|^2 R \,. \tag{14}$$

If $\xi R < 0$ the vacuum with $\chi = 0$ is unstable and the expectation value of χ in the true vacuum state would be

$$\langle \chi^2 \rangle = \xi R / 2\lambda \,. \tag{15}$$

Since the curvature is proportional to the ratio of the trace of the matter energy-momentum tensor to the square of the Planck mass

$$R = -\frac{8\pi}{M_{Pl}^2}\, T \,, \tag{16}$$

in the universe today we have

$$\langle \chi^2 \rangle \approx 10^{-80}\, \frac{\xi}{\lambda}\, \mathrm{GeV}^2 \tag{17}$$

which is negligible for any reasonable value of the ratio ξ/λ. On the other hand, in the early universe, before the radiation dominated epoch, $\langle\chi^2\rangle \sim (\mathrm{TeV})^2$ is certainly achievable, thanks to the possibility of a much lower effective Planck mass and a high energy density. In this picture, the quark mixing angles should be also much different from their standard late time values and the suppression due to the Jarlskog determinant (8) could be absent or much milder.

Since χ is more strongly coupled to quarks one should take care that this field would not contradict the precise electroweak data. It may be probably achieved if χ is an order of magnitude heavier than the usual Higgs, φ, and the coupling to light quarks is not too strong.

4.3 "Third Sakharov Condition": Out of equilibrium criterion

The "third Sakharov condition" for baryogenesis is that the universe be out-of-equilibrium so that any baryon number that is created is not immediately wiped out by other reactions. Inflationary cosmology offers two ways to achieve this criterion: 1) bubble collisions due to a first order phase transition in chain inflation and 2) out-of-equilibrium decays of particles produced during reheating in inflation. We discuss both possibilities here.

4.3.1 Chain Inflation

In chain inflation, a series of tunneling events takes place, e.g., in a potential that looks like a tilted cosine [41, 24]. The field tunnels from one high energy minimum of the potential to a lower energy one, and thence to yet another lower energy minimum until it reaches zero energy. At each stage the universe inflates by a fraction of an efolding, adding up to a total of sixty efolds after several hundred tunneling events. The phase transitions are first order, with bubbles of true vacuum nucleating inside the de Sitter space. Reheating occurs at the last few tunneling events, when bubble collisions of the final true vacuum take place. While these bubble collisions are taking place, the universe is out of thermal equilibrium, so that baryogenesis may take place without allowing the reverse reactions to destroy the baryons that have been created. This mechanism is similar to the bubble collision mechanisms that were discussed for electroweak baryogenesis (should this transition be first order). In addition, the energy difference between minima can be arbitrary, in this case a fraction of a TeV, if the total height of the potential is constrained to be below the TeV Planck scale at the time of inflation, Heavy particles can be produced during reheating, and these can subsequently have baryon violating decays (again, out of thermal equilibrium).

4.3.2 Production of heavy particles

The period of exponential expansion of the universe, known as inflation, ends up with "reheating". As suggested in Ref. [42], such period provides favorable conditions for possible baryogenesis. Many weakly interacting particles can be abundantly created, even very heavy ones. In addition, their reaction rates can be slow and life-time sufficiently long, allowing them to decay out of equilibrium and to give the universe a net baryon number. In standard rolling models of inflation, the reheating proceeds through three different stages: first, there is the preheating period, where the classical inflaton field, $\phi(t)$, oscillates, producing all the particles it couples to; then, the produced particles (if heavy and unstable) decay; last, particles produced during the previous two stages interact with each other and thermalize, converting the universe from a cold and low-entropy state into a hot and high-entropy one. Heavy particles can be created during reheating, even with masses larger than frequency of the inflaton oscillations. Specific mechanisms include tunneling models of inflation (chain inflation, as described in the previous subsection) as well as perturbative, nonperturbative, and gravitational particle production in rolling models as discussed below.

1. Inflaton decay: The inflaton ϕ could perturbatively decay into particles if the sum of their masses is smaller than the effective mass of the inflaton. As usual it is assumed that the energy density of the inflaton is smaller than the Planck one. Hence, for a TeV mass gravity scale, the height of the potential at the beginning of inflation must be below the TeV scale. Most rolling models of inflation with the usual Planckian gravity require potentials with 10^{19} GeV scale widths and GUT scale heights in order to produce the appropriate amplitude of density fluctuations $\delta\rho/\rho \sim 10^{-5}$, so that a TeV Planck mass makes such models untenable. On the other hand, such a situation is not formally excluded and inflation might start with the potential energy of the inflaton much smaller than the effective Planck scale, $\sim$ TeV^4.

Another option is hybrid inflation or models with many scalar fields (e.g. assisted inflation [44]), where smaller mass scales can work. One of the examples considered in Ref. [45] is a hybrid inflation model with compact extra dimensions, where inflation (at least its latest stage) occurs only in our 3-brane and the extra dimensions are already stabilized (though a previous period of inflation both in the bulk and on our brane was certainly needed). The potential of the model is

$$V(\phi,\sigma) = \frac{1}{4V}(M_*^2 - \lambda\sigma^2)^2 + \frac{1}{2}m^2\phi^2 + \frac{\mu^2}{2}\phi^2\sigma^2 \; . \tag{18}$$

The mass of the inflaton field before inflation must be $m \sim 10^{-10}$ eV to obtain density perturbations in agreement with observations. After inflation the mass of the inflaton is $\mu M_*/\sqrt{\lambda} \sim M_*$. If the mass of the inflaton is that high, it could decay via B-nonconserving channels, e.g. $\phi \to 3q\,l$ and $\phi \to 3\bar{q}\,\bar{l}$ with different probabilities, due to CP-violation, and thus the inflaton decays might generate cosmological baryon asymmetry.

2. Nonperturbative particle production by inflaton: The non-perturbative approach was pioneered in papers [46, 47] where it was shown that the production rate that vanishes in the lowest orders of perturbation theory may be significant if non-perturbative effects are taken into account. In particular, production of particles coupled to the inflaton field as

$$h\phi\bar{f}f \;\text{ and }\; \lambda\phi^2 b^\dagger b \; , \tag{19}$$

where f and b are respectively fermionic and bosonic fields, would be only mildly, (as $1/\sqrt{\phi_0}$), suppressed [46], despite a large effective mass of the produced particles introduced by such coupling in the case of large amplitude of the inflaton oscillations

$$\phi = \phi_0 \cos(m_\phi t + \delta) \; . \tag{20}$$

The particles are predominantly produced when ϕ passes through zero [46, 48] and during this (short) time the mass of the produced particles vanishes. However, if in addition to the effective mass induced by the coupling (19) there exists a "normal" mass of the created particles $m_f\bar{f}f$ or $m_b|b|^2$, the production would be strongly, exponentially, suppressed if $m_{f,b}$ is large in comparison with the characteristic frequency of $\phi(t)$ [46]. If so, only light particles would be created but they may acquire masses if the electroweak phase transition took place after the universe (pre/re)-heating. On the other hand, the effective frequency can be large for a large amplitude of the formally massless inflaton field, which can be realized for the potential $U(\phi) = \lambda\phi^4$. A natural upper bound $U(\phi) \leq M_{Pl}^4$ implies $\phi \leq M_{Pl}/\lambda^{1/4}$. Inflation should stop when the effective inflaton mass or frequency of oscillations is of the order of the Hubble parameter, i.e.

$$H^2 = \lambda\phi^4/M_{Pl}^2 \sim \omega^2 = \sqrt{\lambda}\phi^2 \; . \tag{21}$$

In other words the inflaton starts to oscillate and particle production begins when $\omega \sim M_{Pl}$. It means that the particles with masses up the the Planck mass can be created by the inflaton.

In the case of production of bosons parametric resonance is possible [46, 47], which can strongly enhance the production rate in the case of wide resonance [49] and facilitate production of particles with masses exceeding the mass of inflaton.

All the mechanisms described here allow for production of particles with masses which may be much larger than the universe temperature after thermalization. Thus the created massive particles may be out of equilibrium if their life-time is longer than the Hubble time.

3. Gravitational production: Gravitational particle production in time variable metric [50] is efficient only when the Hubble parameter, H, is not too small in comparison with the particle mass. Due to conformal flatness of the cosmological FRW metric, conformally invariant massless fermions and vector bosons would not be created [51], but quantum conformal anomaly eliminates this exclusion and allows for noticeable production of even massless gauge bosons [52].

For models with a time dependent Planck mass, gravitational particle production may be significant. At the end of inflation, the time dependent Planck mass and expansion rate are both $H \sim M_* \sim$ TeV. The particles produced by external gravitational field should have energies and/or masses in the same TeV range. The fraction of the produced heavy particles is model dependent and, in particular, it depends upon the law of relaxation of the gravity scale from TeV to the asymptotic Planck value. If the time dependence of the Newtonian constant is generated by the non-minimal coupling of a scalar field Φ, to curvature [7, 53], $\xi R\Phi^2$, the rate of evolution of $M_*(t)$ is determined by the potential $U(\Phi)$ or, more generally, $U(\Phi, R)$. The effective frequency of $\Phi(t)$ may be easily and naturally in the same TeV range and heavy particles, X, are to be produced. Their number fraction may be noticeable, even close to unity. Moreover, if their life-time is about $\alpha m_X \sim 0.01 m_X$ which is small in comparison with the expansion rate, $H \sim M_*$, they may become dominant, even if their energy density was initially small in comparison with the energy density of relativistic particles. These features could lead to very efficient baryogenesis through B-nonconserving decays of TeV mass particles.

4.4 Generation of a matter-antimatter asymmetry

As is argued in the previous subsections, TeV scale gravity looks favorable for low energy baryogenesis in a slightly modified Minimal Standard Model of particle physics. We argued that all three "Sakharov conditions" are more easily satisfied with a low fundamental scale of gravity.

As shown in Subsection 4.3.2, heavy particles X may be produced after inflation by several reasonable mechanisms. Their relative number density at production is model dependent but in all the cases it is not negligibly small (and in fact in some cases we should take care to not overclose the universe with heavy objects): $r_X = n_X/n_{tot} \geq 10^{-3}$ is a reasonable guess. This result depends upon the concrete scenario of heavy particle, X, production. If they are predominantly created by gravitational field at the end of inflation their energy density can be estimated [50] as $\rho_X/\rho_{tot} \sim const\,(m_X/M_{Pl})^2$ with a constant factor of order unity. Thus this fraction may be close to one. The ratio of the number densities, r_X would be diluted by the entropy released in the inflaton decay by the factor m_X/T_{rh}, where the (re)heating temperature T is expected to be in the GeV to MeV range. This simplified estimate follows from the made above statement that the energy density of the heavy and thermalized particles, created by the inflaton decays, are of the same order of magnitude, i.e. $\rho_X \sim T^4$. Since $\rho_X = n_X m_X$ and $n_\gamma \sim T^3$, we find $n_X/n_\gamma \sim T/m_X$.

One should also keep in mind that the life-time of the created heavy particles is large in comparison with the Hubble time at the moment of the production and their relative energy density rises in the course of expansion with respect to the energy density of relativistic species. This would somewhat increase the effect.

There should also be the entropy suppression factor due to annihilation of massive species in thermal equilibrium universe into photons. If $T_{rh} \sim 1$ GeV this factor is about 0.1. Another small factor comes from the suppression of the CP-odd effects in the branching ratio at the level of $\alpha/\pi \sim 10^{-2} - 10^{-3}$ due to necessity of rescattering in the final state (remember that CP violation arises from the interference of loop diagrams with the tree graph). Taken together, these small factors give the suppression of the baryon asymmetry in the interval $10^{-6} - 10^{-7}$, depending upon the model. As we have argued at the beginning of Sec. 4 the amplitude of CP-violation depends upon the quark mixing angles and in low temperature baryogenesis it should be about $\epsilon_{CP}(T=0) \sim 10^{-5}$. If quark masses vary with cosmic time, the mixing angles may be large in the early universe and ϵ_{CP} may be of order unity both at low and high T.

The estimates presented above are of course very approximate and model dependent but they show that a model with TeV scale gravity and time varying quark masses is quite efficient in creating cosmological baryon asymmetry. Taking all the factors together we expect that the baryon to photon ratio, β, can be easily equal to the measured value [54]:

$$\beta = \frac{n_B}{n_\gamma} = 6 \cdot 10^{-10}\,. \tag{22}$$

5 Conclusion

We have considered baryogenesis scenarios in models where the true quantum gravity scale M_* is in the TeV range. Here, baryon number can be violated by gravitational decays of TeV-particles, which are produced out of thermal equilibrium after inflation and quickly decay through a black hole intermediate state, generating the cosmological matter-antimatter asymmetry.

We would like to stress that a low reheating temperature which possibly excludes a period of unbroken electroweak symmetry is not a problem here but a favorable ingredient of the model, since it prevents dangerous electroweak sphaleron processes capable of washing out previously created asymmetry. Moreover, low T allows for a much larger CP violation from the CKM matrix. In fact, our mechanism cannot work with the standard Planck mass $M_{Pl} \sim 10^{19}$ GeV and superheavy particles with masses of the same order of magnitude. In addition, if M_* is at the level of a few TeV and heavy elementary particles exist, one can possibly test (and therefore to reject or to accept) the model in the next generation of hadron colliders.

If SUSY particles were unstable to decay via these same black holes, then a possible negative consequence of the model would be the instability of the lightest supersymmetric particle (LSP), which may exclude a very nice and testable candidate for cosmological dark matter. However, if our conjecture [38] is true, the life-time of the LSP might still be long enough to provide the dark matter, depending upon the quantum numbers and the mass of the LSP.

Our model requires a minimal extension of the particle content of the standard model. The scenario may operate with the standard set of quarks. We considered TeV gravity models which may provide a resolution to the hierarchy problem between electroweak and gravitational scales, due to either large extra dimensions or time-varying Planck mass. One variation we considered requires time variation of the Planck mass and quark masses created by some new scalar fields.

The value of the baryon asymmetry is model dependent and cannot be predicted precisely since it depends upon many unknowns but the same shortcoming is explicit (or implicit) in all other scenarios of baryogenesis.

We also mention the possibility that other higher dimensional objects, such as string balls, p-branes, or black branes may serve as alternatives to black holes as intermediate states responsible for baryogenesis, though we have not computed any rates for such processes.

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